Detection of Wolf-Rayet stars of WN and WC subtype in Super Star Clusters of NGC 5253[1]

Daniel Schaerer[2,3]

Thierry Contini[4,5]

Daniel Kunth[6]

and

Georges Meynet[3]

ABSTRACT

We present spectroscopic observations of the central star clusters in NGC 5253 the aim of which is to search for WC stars. Our observations show the presence of Wolf-Rayet (WR) stars not only of WN but also of WC subtype in two star forming regions corresponding to the maximum optical and UV emission. The massive star population we derive is consistent with young bursts of $\sim$ 3 and 4 Myr. The region of maximum optical emission is found to provide the dominant contribution of the ionizing flux as opposed to the less extinguished region of maximum UV brightness. The presence of WR stars near the N-enriched regions found by Walsh & Roy (1987, 1989) and Kobulnicky et al. (1997) suggests they are a possible source of N. It is presently unclear whether or not our detection of WC stars is compatible with the normal observed He/O and C/O abundance ratios.

ApJ Letter, in press (Received: 2 November 1996, Accepted: 13 March 1997)

Subject headings: galaxies: individual (NGC 5253) – galaxies: ISM – galaxies: starburst – H II regions – stars: Wolf-Rayet

---

[1]Based on observations obtained at the European Southern Observatory, Chile

[2]Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218; schaerer@stsci.edu

[3]Observatoire de Genève, CH-1290 Sauverny, Switzerland

[4]UMR 5572, Observatoire Midi-Pyrénées, 14 avenue E. Belin, F-31400 Toulouse, France

[5]Present address: School of Physics and Astronomy, Tel Aviv University, 69978 Tel Aviv, Israel; contini@wise.tau.ac.il

[6]Institut d'Astrophysique de Paris, 98 bis Bd. Arago, F-75014 Paris, France

1. Introduction

We have initiated a systematic search program to find Wolf-Rayet (WR) stars of the carbon series (WC subtypes) in the so-called WR galaxies (Conti 1991). Indeed, among the ~ 70 WR galaxies known today only few cases show the broad C IV $\lambda 5808$ emission originating from WC stars (e.g. Mrk 724, NGC 4861, NGC 4214, He 2-10, NGC 2363; cf. references in Meynet 1995). However, as Meynet (1995) pointed out, a natural result of stellar evolution (or our current knowledge of it) is that one expects that in a large fraction of WR galaxies (typically 30 % for metallicities $1/5 \leq Z/Z_{\odot} \leq 1$; cf. Schaerer & Vacca 1996) the WR population should be dominated by stars of the WC subtype if star formation occurs on timescales short compared to the lifetimes of massive stars. Since the C IV $\lambda 5808$ feature is usually weaker than the characteristic WR bump at ~ 4700 Å it may simply have been overlooked in many previous observations. Interestingly, in the homogeneous sample of low metallicity H II galaxies of Izotov, Thuan & Lipovetsky (1994, 1997), 5 out of 15 WR-rich objects show strong WC features, which corresponds surprisingly well to the theoretically predicted value of ~ 30 %. Apart from the implications for the understanding of massive star evolution, the presence or absence of a substantial population of WC stars in young starbursts may imply significant differences of the ionizing spectrum (cf. Schaerer 1996) and the chemical enrichment due to massive stars (cf. Maeder 1983).

As one of our targets we have observed the central region of the amorphous galaxy NGC 5253 at a distance of 4.1 Mpc (Sandage et al. 1994). This low metallicity object ($Z/Z_{\odot} \sim 1/5$) contains a very young starburst and thus provides an important laboratory for studies of local chemical enrichment, or "chemical pollution" in giant H II regions (Walsh & Roy 1987, 1989, hereafter WR87, WR89; Pagel et al. 1992; Esteban & Peimbert 1995; Kobulnicky et al. 1997, hereafter KSRWR97). In addition, recent HST imaging (Meurer et al. 1995; Gorjian 1996; Calzetti et al. 1997) reveals numerous Super Star Clusters in NGC 5253 and make this object an interesting place to study what might be proto-globular clusters (cf. Conti & Vacca 1994; Meurer et al. 1995, and references therein).

In this Letter we report the detection of WR stars of both WN and WC subtype in two star forming regions of NGC 5253. The observations are presented in § 2. In § 3 and § 4 we determine the massive star content of the two regions and ages of the populations. The implications regarding the source of ionization of NGC 5253, the hardness of the ionizing flux, and the origin of N enrichment are discussed in § 5.

2. Spectroscopic observations

Long-slit spectra of NGC 5253 were obtained on the night of 1995 April 24 – 25 at the ESO[7] 2.2m telescope. The data were acquired with the EFOSC2 spectrograph and a 1024×1024 Thomson CCD with a pixel size of 0.34″. During the photometric night we also observed the spectrophotometric standard stars HD 84937 and Kopff 27 in order to flux calibrate the spectra of the galaxy. We used grism 4 which gives a spectral coverage of 4400 – 6500 Å with a resolution of ~ 5 Å. The slit was oriented NNE-SSW (PA $\sim 20°$) in order to lie the brightest optical regions of the galaxy. The slit width was 1.6″ for the galaxy observations and 5″ for the standard stars. Spectra of He-Ar calibration lamp were obtained immediately before and after the galaxy integrations in order to accurately calibrate the wavelength scale. The total integration time of 5400 s was divided into 5 exposures (4 times 20 minutes plus 10 minutes) in order to avoid saturation of the bright nebular lines (Hβ and [O III]) and to recognize cosmic ray impacts. The seeing was relatively stable during the observations with a mean spatial resolution of about

[7] European Southern Observatory, La Silla, Chile

1″. The spectrum was aquired at low airmass ($\sim$ 1.1) and no correction for the loss of blue light due to atmospheric dispersion was made.

The spectra were reduced according to standard reduction procedures using the MIDAS package LONG. These include bias subtraction, flat-field and airmass corrections, wavelength and flux calibrations, sky subtraction, and cosmic ray removal. The spatial distribution of emission-lines along the slit reveals the presence of two bright regions, hereafter called A (for the brightest) and B (south of A), separated by about 3″ (60 pc at a distance of 4.1 Mpc). Comparisons of our slit position with the HST images of Meurer et al. (1995, FOC with F220W filter) and Gorjian (1996, WFPC2 with F606W) show that region A is located at the maximum of the optical emission (=region 1 of Gorjian), while B is centered on the maximum peak of UV emission (=UV1 of KSRWR97). Note that region 1 of WR89 (=region A of WR87) contains both our regions A and B. We also detected a region (hereafter called H), located $\sim 3''$ NNE of A, for which no clear counterpart could be found in the HST images. We extracted one-dimensional spectra corresponding to the different regions by adding 3 columns ($\simeq 1''$) along the spatial dimension.

The two regions A and B are bright, low-metallicity H II regions with a large number of intense nebular emission lines seen in their spectra. Because of the medium spectral resolution, the emission lines in the WR bumps at $\sim$ 4700 and 5800 Å (see Fig. 1) and the [O I]/[S III] lines at 6300 Å are not well separated. In order to measure accurately the individual emission lines, we use a procedure of multi-gaussians fitting where the number of gaussians is the only fixed parameter (position, intensity and FWHM are free to vary). Line fluxes, FWHM and equivalent widths were determined using MIDAS standard commands. Due to the limited spectral range, our observations do not include the Hα emission line commonly used to determine the internal reddening parameter C_β. For regions A and H we therefore adopt $C_\beta = 0.44$ and 0.85 respectively, taken at the appropriate locations from the extinction map of WR89. For B we adopt the reddening derived by KSRWR97 ($C_\beta = 0.20$)[8]. Dereddened fluxes are derived using the extinction law of Seaton (1979) including a Galactic foreground extinction of E(B-V)=0.05 (Burstein & Heiles 1984). Observed and dereddened fluxes are given in Table 1. The relative uncertainty of our measurements is smaller than 10% for the most intense lines (Hβ and [O III]), and can reach about 40% for the faintest. We note that our absolute flux calibration for region A agrees well with the values measured by Campbell, Terlevich & Melnick (1986; hereafter CTM86) and WR89.

Up to three different broad emission lines (FWHM $\geq$ 30 Å) have been detected with varying confidence levels in regions A and/or B over the wavelength range covered by our spectra: the N III/C III $\lambda\lambda$4640,4650 blend, He II λ4686, and C IV λ5808-5812. Clear detections ($\geq 3\ \sigma$) of broad lines are C IV in A and B and He II λ4686 in B. The detection and hence the FWHM of He II λ4686 in the spectrum of A dominated by high-excitation nebular emission lines of [Ar IV] $\lambda\lambda$4711,4740 (see Fig. 1) is uncertain ($\sim 2\sigma$). N III/C III$\lambda\lambda$4640,4650 may be present in A and B at a 1-2 σ level. Region H stands out with a very large He II λ4686/Hβ ratio, uncommon for the metallicity of NGC 5253, and a relatively narrow He II λ4686 line (FWHM=20 Å). Due to these peculiarities and the absence of a visible counterpart in any images (cf. above) this region is not discussed further. Future studies would be highly desirable.

The broad WR bump around 4700 Å has been previously detected by CTM86 , WR87 in their region 1 (containing both our regions A and B), and in the region UV1 (=our B region) of KSRWR97. One of the main results of this

[8]Note that highly spatially variable extinction has been suggested in NGC 5253 by KSRWR97 and Calzetti et al. (1997). IR and radio observations from Beck et al. (1996) show larger extinction than the optical data.

Letter is the unambiguous detection of a broad (FWHM = 62 and 86 Å) C IV λ5808 emission line in regions A and B (see Fig. 1), which clearly indicates the presence of WC stars in these regions (see § 3). A sufficiently high S/N is required for the detection of the C IV λ 5808 line in integrated spectra of extragalactic H II regions or alike objects, and to derive the observed frequency of WC stars in WR galaxies. This explains the non detection of this line in previous ground-based spectra of NGC 5253 (CTM86, WR87, WR89) and in the recent HST FOS spectrum of the region UV1 of KSRWR97. Interestingly, however, the presence of WC stars was suspected by WR89 based on a high carbon abundance derived from IUE spectra (cf. §4).

3. The origin of the broad emission lines in regions A and B

Both from the relative strength of He II λ4686 to C IV λ5808 and from the large FWHM of the latter line, WN stars can be ruled out as the origin of the C IV line. The observed FWHM ($\sim$ 70 Å) of this line corresponds well to early type WC stars (typically WC4; Smith, Shara & Moffat 1990) including possibly also some WO3-4 stars: their O V λ5590 emission (< 15 % of C IV λ5808) would remain undetectable. From the absence of O V λ5590 a significant number of WO1-2 stars can be excluded (cf. Kingsburgh, Barlow & Storey 1995). Similarly the absence of C III λ5696 excludes a significant population of late type WC stars. The relative contributions of the N III/C III $\lambda\lambda$4640,4650 blend and He II λ4686 to the WR bump exclude a pure WC origin. The FWHM ($\sim$ 30 Å) of He II λ4686 agrees well with WNL stars (Smith, Shara & Moffat 1996). All broad emission line features therefore indicate a mixed population of WNL, and WC4 and/or WO3-4 stars in regions A and B. This result is further supported by quantitative comparisons presented in § 4. The presence of intermediate type WN/WC stars cannot be excluded.

4. The Wolf-Rayet and O star population in NGC 5253

The approximate number of O and WR stars present in the observed regions can be estimated as follows. Adopting the value $\log Q_0 = 49.05$ from Vacca & Conti (1992, hereafter VC92) for the Lyman continuum luminosity of a O7V star and assuming Case B recombination, we estimate $\sim$ 865 (210) O7V stars in region A and in region B from their Hβ luminosity. These numbers are approximately $\sim$ 5 and $\sim$ 35 % lower, respectively, if we account for the contribution of the WR stars to the ionizing flux. Depending on the age of the population and the IMF slope, the number of O7V stars does not necessarily correspond well to the total number of O stars: most likely the total number of O stars is larger by a factor of $\sim$ 2 and 4 for A and B respectively (Schaerer 1996). Using the average observed luminosity of WC4 stars in the C IV λ5808 line ($L_{5808} = 2.5 \times 10^{36}$ erg s^{-1}; VC92), the 5808 emission in regions A and B can be explained by 10 and 13 WC4 stars respectively. From the observed He II λ4686 line luminosity we derive an upper limit of 25 WNL stars for A (depending on nebular contribution) and 39 WNL stars for B, using the average line luminosity given by VC92.

To see whether the WNL, WC and O star populations are compatible with predictions from stellar evolution we use the recent evolutionary synthesis models of Schaerer (1996) and Schaerer & Vacca (1996), which allow direct comparisons to be made with the relevant observational quantities related to the WR and O star population (Fig. 2 panels b-d). The predictions are shown for instantaneous burst models at the appropriate metallicity for regions A and B (Z=0.004, cf. WR89, KSRWR97), assuming a Salpeter IMF with an upper mass cut-off of $M_{\rm up} = 120$ $M_\odot$. The observed line fluxes in the different WR lines (in units of the Hβ flux) are shown as filled symbols. Panel **a** illustrates the corresponding WR/O, WNL/O, and WC/O number

ratios. Figure 2 shows that both the observed values of the WR lines fluxes and their variation with $W(\mathrm{H}\beta)$ can be reasonably well reproduced by the models for Z=0.004. With several variations of the input parameters (flatter IMF, short burst duration, etc.) all the observed values can be matched with greater accuracy. In view of the uncertainties of the measurement for these weak lines we conclude Hβ and all broad WR lines in both regions *A* and *B* are consistent with an approximately instantaneous burst. The strong WR features also imply the presence of very massive stars ($M_{\mathrm{initial}} \geq 60\ M_{\odot}$).

In the burst models a decrease of $W(\mathrm{H}\beta)$ corresponds to an increasing age of the burst. The ages derived from our models correspond to ~ 2.8 Myr for *A* and 4.4 Myr for *B*. As shown above this age sequence is also compatible with the WR line fluxes, which exhibit changes on short time scales. The non-detection of radio emission from SNR in NGC 5253 supports the presence of very young nuclear starbursts (less than 1-2 10^{7} yr, Beck et al. 1996).

5. Discussion

Does the presence of WC stars lead to the high excitation of the gas, and thus the nebular He II emission as suggested by Schaerer (1996) ? At the age of region *A* (estimated from its large value of W(Hβ)) the models of Schaerer (1996) predict an important *nebular* contribution to the total He II λ4686 emission due to the large fraction of WC stars in the burst. Given the weakness of the 4686 line in this region, its width is quite uncertain. The presence of strong nebular lines of [Fe III] λ4658 and [Ar IV] $\lambda\lambda$4711,4740 indicating high excitation resembles closely the cases of Pox 4 (cf. Kunth & Sargent 1981; VC92) and Mkr 1271 (Contini 1996) where the distinction between broad stellar and nebular He II is unclear. The observations of region *A* are thus compatible with WC stars as the origin of nebular He II emission. At the age corresponding to region *B* the models of Schaerer (1996) predict only broad He II emission, in agreement with the observations. Compared to *A*, the weakness of the forbidden Ar IV lines also indicates a lower excitation.

The analysis of the stellar population in regions *A* and *B* sheds further light on the ionizing source of NGC 5253 and has important implications for scenarios of local chemical enrichment.

The ionizing clusters: As pointed out by KSRWR97 the brightest UV cluster (their UV1 which is included in our region *B*) does not provide enough ionizing flux to explain the Hα surface brightness of NGC 5253 corresponding to $\sim 4 \times 10^{52}$ photons s^{-1} (Martin & Kennicutt 1995) derived assuming a constant extinction of $C_{\beta} = 0.47$. Our observations, however, clearly reveal that region *A* (corresponding to the optical maximum and also approximately to the Hα emission peak) contains a larger number of O stars than region *B*. From Hβ we obtain an ionizing Lyman continuum flux of 9.7×10^{51} and 2.4×10^{51} photon s^{-1} for regions *A* and *B* respectively. Region *A* is of higher extinction and thus clearly dominates the production of ionizing photons as compared to the brightest region in the UV. In view of the possible underestimation of extinction (cf. Beck et al. 1996) and the strong spatial extinction variations (KSRWR97, Calzetti et al. 1997) we suspect that the close area surrounding region *A* (possibly including also *H*) may well produce enough ionizing photons to explain the total observed Hα surface brightness.

WR stars and the chemical enrichment: Local overabundance of nitrogen in several regions of NGC 5253 is well established (WR87, WR89, KSRWR97). The recent HST observations of KSRWR97 show N enrichment in two locations (called HII-1 and HII-2) close to the peak of Hα emission (= our region *A*), while N/O in their region UV1 (included in our region *B*) seems to be typical for metal-poor galaxies. Assuming that WR stars eject a significant amount of nitrogen, our likely detection of WR stars in *A* provides a plausible source of N in the very proximity of

the N-enriched regions. Region A, overlooked by KSRWR97 due to its low UV brightness, is thus most likely the "hidden" cluster containing the sources of the observed pollution.

More generally, the detection of WR stars of both WN and WC subtypes in both of our regions raises several questions. The earlier finding of a possible carbon overabundance by WR89, which originally lead these authors to suggest the presence of WC stars, was not confirmed by the results of KSRWR97. If the overabundance of N (in the regions close to A) is due to WN stars, why are the ejecta of WC stars (presumably mostly He, C and O) not detected ? Furthermore, why does region B (=UV1), which also harbours WR stars, not show any significant overabundance ? Abundance differences between these two regions might be related to their age difference: maybe mixing processes in B had time to dilute the ejecta with the ambient medium, whereas the younger region A is currently in a phase of heavy pollution. Hopefully a study of NGC 5253 will not only tell us its history of star formation but also more about still poorly understood nucleosynthetic yields in massive stars and mixing processes in the ISM.

DS thanks Daniela Calzetti, Rosa González-Delgado, Claus Leitherer, Gerhard Meurer, and Bill Vacca for stimulating and useful discussions. DK thanks Eline Tolstoy for a careful reading of the manuscript. Daniela Calzetti also kindly provided us with HST images of NGC 5253. DS acknowledges a fellowship from the Swiss National Foundation of Scientific Research and partial support from the Directors Discretionary Research Fund of the STScI.

REFERENCES

Beck, S.C., Turner, J.L., Ho, P.T.P., Lacy, J.H., Kelly, D.M., 1996, ApJ, 457, 610

Burnstein, D., Heiles, C., 1984, ApJS, 54, 33

Campbell, A., Terlevich, R., Melnick, J., 1986, MNRAS, 223, 811

Calzetti, D., et al., 1997, in preparation

Conti, P., 1991, ApJ, 377, 115

Conti, P., Vacca, W.D.W., 1994, ApJ, 423, L97

Contini, T., 1996, in "WR stars in the Framework of Stellar Evolution", 33rd Liège Int. Astroph. Coll., Eds. J.M. Vreux et al., p. 619

Esteban, C., Peimbert, M., 1995, A&A, 300, 78

Gorjian, V., 1996, AJ, 112, 1886

Izotov, Y.I., Thuan, T.X., Lipovetsky, V.A., 1994, ApJ, 435, 647

Izotov, Y.I., Thuan, T.X., Lipovetsky, V.A., 1997, ApJ, in press

Kingsburgh, R.L., Barlow, M.J., Storey, P.J., 1995, A&A, 295, 75

Kobulnicky, H.A., Skillman, E.D., Roy, J.R., Walsh, J.R., Rosa, M.R., 1997, ApJ, in press (KSRWR97)

Kunth, D., Sargent, W.L.W., 1981, A&A, 101, L5

Maeder, A., 1983, A&A, 120, 113

Martin, C.L., Kennicutt, R.C., 1995, ApJ, 447, 171

Meurer, G., Heckman, T.M., Leitherer, C., Kinney, A., Robert, C., Garnett, D.R., 1995, AJ, 110, 2665

Meynet, G., 1995, A&A, 298, 767

Pagel, B.E.J., Simonson, E.A., Terlevich R.J., Edmunds, M.G., 1992, MNRAS, 255, 325

Sandage, A., Saha, A., Labhardt, L., Schwengeler, H., Panagia, N., Macchetto, F.D., 1994, ApJ, 423, L13

Schaerer, D., 1996, ApJ, 467, L17

Schaerer, D., Vacca, W.D.W., 1996, in "WR stars in the Framework of Stellar Evolution", 33rd Liège Int. Astroph. Coll., Eds. J.M. Vreux et al., p. 641

Seaton, M.J., 1979, MNRAS, 187, 73p

Smith, L.F., Shara, M.M., Moffat, A.F.J., 1990, ApJ, 358, 229

Smith, L.F., Shara, M.M., Moffat, A.F.J., 1996, MNRAS, 281, 163

Vacca, W.D., Conti, P., 1992, ApJ, 401, 543

Walsh, J.R., Roy, J-R., 1987, ApJ, 319, L57 (WR87)

Walsh, J.R., Roy, J-R., 1989, MNRAS, 239, 297 (WR89)

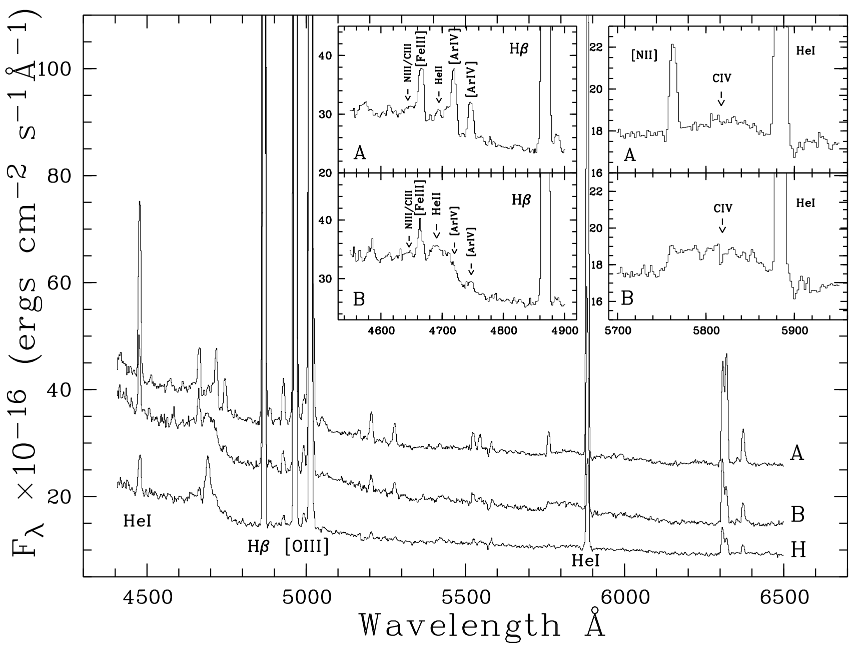

Fig. 1.— Optical spectra of regions *A* (offset of +10 in flux units), *B* and *H* in NGC 5253. The insets show enlargements on the Wolf-Rayet bumps around 4700 Å and 5800 Å for regions *A* and *B*. The broad C IV λ5808 line from WC stars is detected in *A* and *B*. The broad He II λ4686 line from Wolf-Rayet stars is clearly detected in *B* but is suspicious in *A* where the spectrum is dominated by high-excitation nebular emission lines of [Ar IV] and [Fe III]. Note the bright nebular He II line in the spectrum of region *H*. These spectra are not corrected for extinction

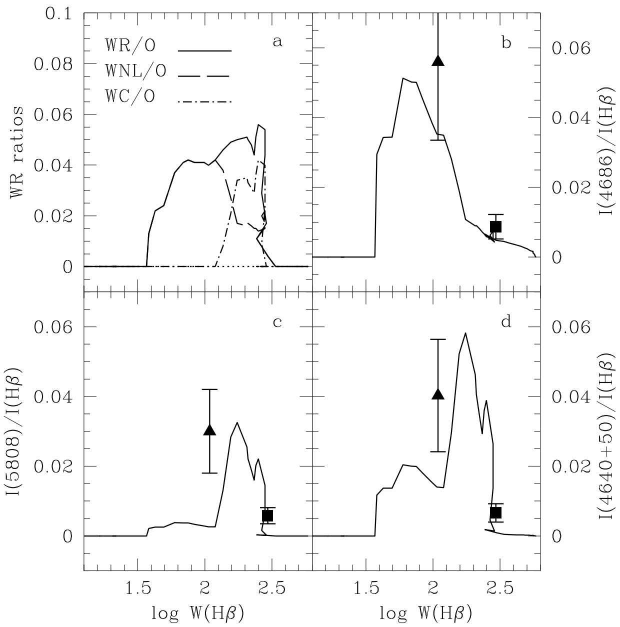

Fig. 2.— The predicted evolution of massive star populations and emission-line ratios from evolutionary synthesis models as a function of the Hβ equivalent width. All models are given for Z=0.004, assuming an instantaneous burst and a Salpeter IMF with $M_{\rm up} = 120\ M_{\odot}$. Observations for regions A and B are shown by squares and triangles respectively in panels b-d. The error bars correspond to the estimated uncertainty of $\pm$ 40 % typical for weak lines. **a.** Total WR/O number ratio (solid), WNL/O (dashed), and WC/O ratio (dashed-dotted). **b.** Ratio of the predicted (He II 4686/H$_\beta$) flux. **c.** Same as b for C IV 5808. **d.** Same as b for the N III+C IV blend at 4640-4650

Table 1

Normalized Flux of Emission Lines in Three Knots of NGC 5253

Line	λ (Å)	A F_λ	A I_λ	B F_λ	B I_λ	H F_λ	H I_λ
He I	4471	45.8	52.1	36.0	38.4	55.2	69.8
N III/C III[a]	4645	(6.2)	(6.7)	(39.3)	(40.7)	(35.4)	(40.1)
[Fe III]	4658	13.0	13.8	19.1	19.8	22.7	25.5
He II[a]	4686	8.3	8.8	54.8	56.3	150.3	166.3
[Ar IV]	4711	16.1	16.9	(21.9)	(22.3)	(48.3)	(52.6)
[Ar IV]	4740	10.1	10.5	(10.8)	(11.1)	(12.7)	(13.6)
He I	4922	10.0	9.8	10.9	10.7	10.1	9.7
[O III]	4959	2123.0	2059.7	1564.1	1538.8	1779.4	1685.1
[O III]	5007	6375.6	6103.1	4695.2	4589.0	5322.4	4917.1
[N I]	5199	7.4	6.7	7.4	7.0	...	...
[Fe III]	5271	4.8	4.2	6.4	6.0	...	...
[Cl III]	5518	4.0	3.3	4.6	4.1	...	...
[Cl III]	5538	2.9	2.4	...	...	...	...
[N II]	5755	5.4	4.3	(2.8)	(2.4)	...	...
C IV[a]	5808	7.2	5.6	33.0	29.0	...	...
He I	5876	142.2	109.5	127.6	111.0	126.9	79.2
[O I]	6300	26.8	19.0	34.7	28.8	33.5	17.9
[S III]	6312	40.2	28.4	24.7	20.6	22.1	11.8
[O I]	6364	8.8	6.2	10.5	8.7	10.0	5.2
C_β		0.44		0.20		0.85	
$W(H\beta)$		294		109		87	
$F(H\beta)$		70.6	229.8	29.8	55.8	13.1	109.6

[a]Broad emission lines (FWHM $\geq$ 20 Å) from Wolf-Rayet stars.

Note.—For each emission-line we reported the observed (F_λ) and dereddened (I_λ) flux normalized to $H\beta \times 1000$. Values in brackets are uncertains. C_β is the extinction coefficient, $W(H\beta)$ is the equivalent width of Hβ in Å and $F(H\beta)$ are the absolute observed and dereddened flux of Hβ emission-line in 10^{-14} erg cm^{-2} s^{-1}.